DEVELOPMENT AND COMMISSIONING OF A CALORIMETER FOR TESTING THE THERMAL PERFORMANCE OF LUMINAIRES

BY

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ABSTRACT

The goal of this project was to design, construct and commission a calorimeter for testing the thermal properties of state-of-the-art luminaires. The calorimeter was built to serve as a testing facility in the Lighting Research Laboratory at the University of Kansas School of Engineering. The calorimeter was designed to approximate a room to achieve testing results that could be applicable in the actual applications. The calorimeter is a highly insulated box (1990 mm x 740 mm x 1915 mm) equipped with six temperature sensors to measure temperature at the air intakes, exhausts and in the center of the calorimeter and two anemometers to measure the air flow rate running through the ceiling cavity and room cavity. Luminaires will be installed in the calorimeter for testing their thermal performance. With a two-cavity-layout and a material of choice separating the two cavities, the calorimeter allows for the one-dimensional analysis of heat distribution. Using data from the temperature sensors and the air flow rate, the heat released by the luminaires to the ceiling cavity and the room cavity can be calculated respectively. Due to its mobility, the calorimeter can be used in different environments such as a temperature-controlled room. Later in a commissioning process, the calorimeter's accuracy was tested using a controllable heat source. A cartridge heater with an adjustable heat output was used to compare to the heat measured by the calorimeter. The results show that the calorimeter has an error of 11% for testing the cartridge heater which approximates equivalent 50W of comparable luminaires. The error decreases with increased cartridge heater wattages. Results for a 114 W energy input show an error of less than 1%.

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1 Introduction

After decades of striving to maximize energy efficiency, one major focus is decreasing the use of energy in built environment. However, there is still much room for improvement. New materials and technologies allow us to construct more energy efficient buildings. Both, the heating, ventilating and air conditioning (HVAC) and lighting systems are two major contributors to the total energy demand of a building. These two systems have both been analyzed individually and improvements have been made, e.g., condensing boilers and the light emitting diode technology. However, the two fields still remain relatively separated. Usually, engineers either specialize in HVAC and plumbing design or electrical and lighting design, though there might be a common denominator.

LED light sources are generally considered to be very energy efficient, as they have a relatively high lumen output compared to the electric energy input. Less commonly known, however, is that only 15-25 percent of the energy input is initially emitted as light and eventually absorbed and converted to heat (see Figure 1). The majority, 75-85 percent is emitted (through conduction and convection) as heat (US Department of Energy, 2007).

Power Conversion for "White" Light Sources

	Incandescent[†] (60W)	Fluorescent[†] (Typical linear CW)	Metal Halide[‡]	LED[*]
Visible Light	8%	21%	27%	15-25%
IR	73%	37%	17%	~ 0%
UV	0%	0%	19%	0%
Total Radiant Energy	81%	58%	63%	15-25%
Heat (Conduction + Convection)	19%	42%	37%	75-85%
Total	100%	100%	100%	100%

[†] IESNA Handbook [‡] Osram Sylvania

[*] Varies depending on LED efficacy. This range represents best currently available technology in color termperatures from warm to cool. DOE's SSL Multi-Year Program Plan (Mar 2006) calls for increasing extraction efficiency to more than 50% by 2012.

Figure 1: Power Conversion for "White" Light Sources (US Department of Energy, 2007)

LEDs, compared to other light sources, have one distinct feature. They do not radiate much heat (if they are fully functional) in the forward direction along with the light. The majority of heat is released through a heat sink mounted on the back of the LED. So far, this heat generated by LEDs has not been put to direct use for space conditioning. A plausible idea is to integrate the luminaires (LEDs) into the HVAC system yet needs further validation in laboratory experiments and field tests. This way the heat could be used to condition the supply air. In winter for heating the supply air and in summer for the required reheating of the chilled air as part of humidity control. (Cai, 2016)

To develop a technology that allows the integration of luminaires into the HVAC system, a thorough study of the heat emitted by light sources and its distribution into the nearby indoor environments, including ceiling cavity and room cavity, is needed. To measure the heat emitted by light sources and dissipated into the environment, a special instrument called calorimeter is needed. In most cases, a calorimeter is a well-insulated box that provides a well-definable, controlled environment. This allows measuring the emitted heat under different conditions. Preferably, it has low mass to allow each test to approach steady state swiftly.

1.1 Background

For understanding the good use of calorimeter in thermal performance evaluation of start-of-the-art luminaires, it is necessary to give some insight into the technology of both the calorimeter and LEDs which will be tested in the calorimeter.

1.1.1 LED Luminaires and their thermal performance

The so-called "father of LEDs" is Nick Holonyak Jr. who invented the first red LED in 1962. (Cai, 2017) For general lighting purposes, the LED technology has only been used in the last decade due to the difficulty of creating white light LED sources. LEDs fall under the category of Solid State Lighting and they can emit infrared, ultraviolet and visible light. The market for LEDs is still comparably small, but is growing quickly.

LEDs are made out of a multi-layer semiconductor material, e.g., aluminum indium gallium phosphide or indium gallium nitride. There are three types of layers in an LED:

- N-type Layer: This layer has an excess of electrons
- P-type Layer: This layer has too few electrons. The lack thereof is referred to as "holes"
- Active Layer: This layer forms at the junction of the N- and P-Type layers.

The process by which LEDs produce light is called electroluminescence. In contrast to traditional light bulbs which create photons through incandescence, photons are generated by an electric current. As shown in figure 2, through the application of an external DC voltage, electrons and holes combine at the active layer. Each time one of the "holes" is filled, the electron falls to a lower energy state. The excess energy is emitted as a photon (see Figure 2).

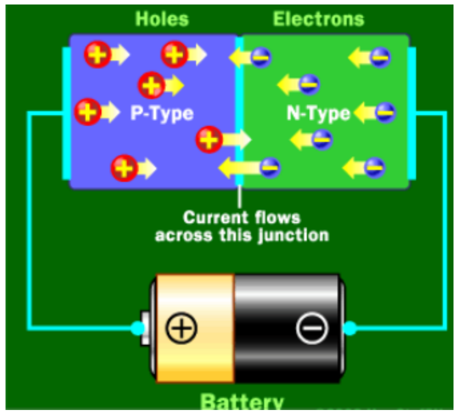


Figure 2: LED function principle (Harris & Fenlon, 2002)

The process just described is the ideal case. However, the electron finding a hole does not always cause a photon to be emitted. The excess energy of the electron is sometimes also released as heat. This heat is not being radiated like the photons; it stays in the LED diode itself. This causes the LED to heat up. For reliability, the maximum temperature that a LED could reach is 120°C (Hui, 2017). To guarantee that this temperature is not being exceeded, the heat generated by "unsuccessful" unification of an electron and a hole needs to be transferred away from the LED. This is being realized through a heat sink that is part of the LED. The heat sink, shown in Figure 3, is a heat exchanger with a high surface area that allows heat to dissipate through convection and radiation to the surroundings.

Figure 3: example commonly used Heat sink (LiFong(HK) industrial Cp., Limited, 2017)

In the past, lighting and HVAC systems could not be integrated and always operated separately mostly due to two main technical limitations:

- Traditional light sources generate light and heat in a mixed energy flux to the same direction
- Traditional light sources are usually too big and clumsy to be integrated into HVAC systems

The latest LED technology has overcome those limitations. LEDs have a high light output and keep a small size at the same time. The light of LEDs is generated in the forward direction, while the heat generated by LEDs is being trapped in the back of the LED. This means that the generated light and heat by LEDs is separated thus do not have a mixed energy flux like the conventional light sources do. Therefore, the chance for integrating the LEDs into an (existing) HVAC system are lifted (Cai, 2016).

Current LED fixture, however, tend to capture the heat in the back of the LED. This makes it hard to use the heat created by the LED. With a redesign of the LED luminaire (see Figure 4), effectively harvesting the heat will be possible (Cai, 2016). The LED luminaires can then be used for (Cai, 2016):

- Reducing the overall lighting energy use
- Reducing the space heating load
- Reducing the space cooling load (using the LEDs for reheating the chilled air)

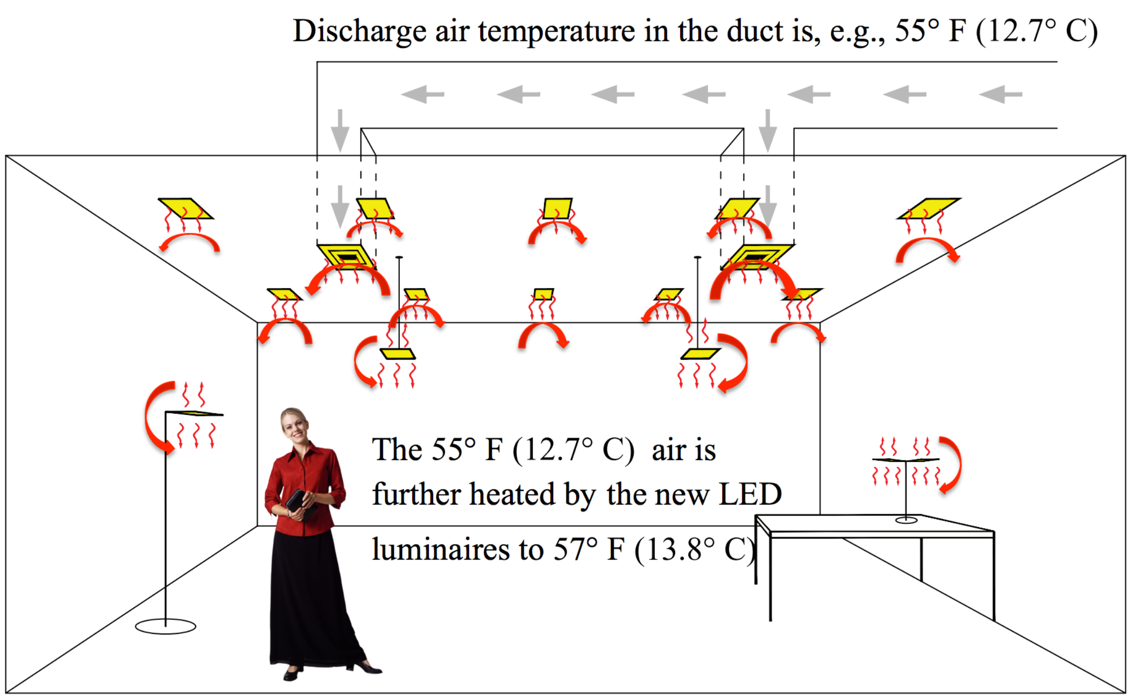


Figure 4: Combined LED lighting and air-conditioning system (Cai, 2016)

1.1.2 Calorimeters

A calorimeter is a tool used to perform calorimetry. Calorimetry is a method to measure the heat released or absorbed during a (chemical) reaction. The term is usually associated with the field of chemistry. There are various different types of calorimetry's that exist. Some of the more common ones are (Texts, Libre, 2015):

- Calorimetry with constant pressure
- Bomb Calorimetry
- Solution Calorimetry
- Scanning Calorimetry
- Gas/Water adsorption calorimetry

These calorimeters are all used to analyze an aspect of a chemical reaction. The calorimeter that is going to be built as part of this project will measure the heat released through imperfect unification of electrons and "holes" in an LED chip. The major difference here is that not just the reaction will be analyzed, but that the whole LED fixture will be analyzed and that there will also be other sources of heat (e.g., the LED driver) that contribute to the total heat output measured by the calorimeter.

1.2 Literature Review

Lighting systems are an important part of the thermal load of a built environment. They are one of the major contributors to the overall heating and cooling load of a building. In chapter 18 of the 2013 ASHRAE Handbook Fundamentals (American Society of Heating, R. a. A. E., 2013), two methods of determining the building cooling load are introduced: the radiant time series and the heat balance method. The radiant time series is a simplified method derived from the heat balance method. Part of the cooling load calculation with both of these methods is the heat gain through luminaires, their radiative / convective split and the ceiling / plenum split of those luminaires. The 2013 ASHRAE handbook provides information about these values for traditional lighting systems (incandescent, fluorescent). Values for the growing market of LED technology are not being provided.

In the past, different approaches have been made to determine the luminaire heat output, the radiative / convective split and the ceiling plenum split. (Ball & Green, 1983) used a mathematical model to compute cooling loads created by lighting for a variety of building-lighting arrangements. The model is based on empirical coefficients from lighting energy-transfer experiments and uses well-known heat exchange computation procedures.

(Chung & Loveday, 1998) used a similar approach to (Ball & Green, 1983). Their model considers all forms of heat transfer (conduction, convection and radiation) of a luminaire in a room. It can be used to calculate temperatures, cooling loads and light levels at any point in a room. The numerical model was verified by field tests in a test cell.

(Mitalas, 1973) and the Division of Building Research of the National Research Council of Canada built a full-size calorimeter room to analyze the cooling load caused by light. They used 4-inch foam plastic insulation covered with plywood on the outside and aluminum foil on the inside. To prevent any heat transfer to the outside, air with the same temperature as the wall temperature was circulated in a space behind the insulated walls. Heat in the room was being removed by chilled water. The heat gain in the room was determined through the temperature change of the chilled water.

(Treado & Bean, 1992) created a test facility similar to the one by (Mitalas, 1973). There are only two major differences in their approach. The size of their room calorimeter is larger than the one constructed by the National Research Council of Canada. To calculate the cooling load, they did not use the temperature increase of chilled water, but the temperature difference between the supply air and return air and the mass flow of air.

(Chantrasrisalai & Fisher, 2007) also created a room calorimeter and used the temperature difference between supply and return air to calculate the cooling load. In addition, they installed a net radiometer to be able to calculate the radiative / convective split. The results of their research are published in the ASHRAE Handbook Fundamentals Chapter 18 for calculation of the cooling load with the heat balance method and the radiant time series method (American Society of Heating, R. a. A. E., 2013).

(Liu, Zhou, Zhong, Huynh, & Maxwell, 2017) applied the same method as (Chantrasrisalai & Fisher, 2007). Instead of traditional luminaires, they used LED luminaires in their room calorimeter to measure the cooling load, radiative / convective split and ceiling / plenum split.

1.3 Goal

The goal of this thesis research is to explore the "Calorimeter for Luminaires" and validate the uses of calorimeter in the measurement of heat generated by the state-of-the-art luminaires, especially LED luminaires. The thesis covers the reasons for a calorimeter, the initial design ideas and reasons behind those ideas, the construction process with all design changes and adaptions, the technology used to operate and analyze the calorimeter and the commissioning process and results. Readers should get an understanding of the calorimeter and how it functions. Additionally, this thesis study will evaluate the planning and construction process of the calorimeter and search for possible optimizations and/or changes for a second edition calorimeter.

1.4 Motivation

To understand why the project of building a calorimeter is being conducted, it is important to look at different variables that influence the room climate. These variables can be divided into different groups, including overall climate (e.g., the climate zone of the location), surrounding environment (e.g., building height and shadow from nearby buildings), the room itself (building type, room volume, room height…), occupants (number, type, activity level…), mechanical system equipment (e.g., computers, printers) HVAC system (type, air flow rate, supply air temperature…) and lighting system (Cai, 2016).

In particular, there are different factors that influence the heat gain through the lighting system. These factors are (Cai, 2016):

- Lighting Power Density
- Lighting Control Schedule
- Luminaire type (ceiling recessed, surface mounted, pendent)
- Number of LED lights isolated
- Number of LED integrated diffusors
- Type of LEDs (RGB mixed vs. phosphor converted)
- Layout of LED lighting and HVAC fixtures
- LED wattage
- LED junction temperature
- Radiative / Convective split
- The conditioned space / ceiling plenum split
- Downlight aperture size

Energy Plus is a simulation software that allows whole building energy simulation (EnergyPlus). The influence of the Lighting Power Density and the Lighting control schedule on the room condition can be simulated in Energy Plus. Other factors, as basic as the luminaire type, however, cannot be simulated in Energy Plus. These variables have an influence on the room climate and it is important to evaluate their influence on the room climate. The calorimeter will allow us to conduct research on most of these variables.

2 Calorimeter design

Due to the goal of the calorimeter allowing researchers to replicate a typical room in a built environment, it was important to design the calorimeter accordingly. In interior lighting design and practice, rooms are usually divided into three cavities: the ceiling cavity, the room cavity and the floor cavity (Lindsey, 1997). In the case of the calorimeter, the decision was made to only include two cavities (see Figure 5) in the calorimeter to simplify the construction because room cavity and floor cavity could be combined in the evaluation of heat generated downwards by the luminaires. From a technical standpoint, the goal is only to find out how much heat is being released by the luminaires and most of the cases the upwards and downward directions of the release; i.e., if the heat is traveling up to the ceiling cavity or down to the room and floor cavity. This also makes the calorimeter construction easier and more cost effective.

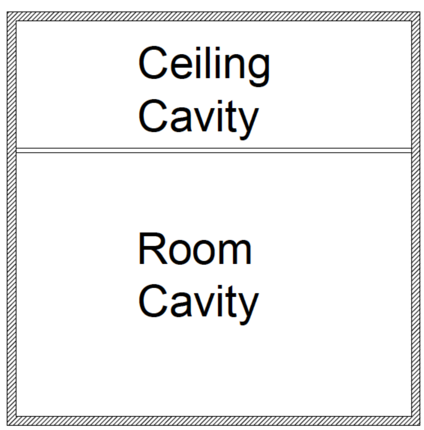


Figure 5: Calorimeter Cavity design

As shown in the illustration above, the calorimeter is divided into two cavities. The two cavities are being separated by exchangeable different types of a ceiling tile depending on the research tasks that will be conducted. The luminaires can be installed in the ways typical for mounting a luminaire with the help of the cavity separator (e.g., recessed, surface mounted, pendant, etc.).

A second requirement for the calorimeter is being mobile, so it can be used in different test environments in multiple laboratories at the University of Kansas School of Engineering, including a darkroom for lighting simulations and tests where an LED workshop is located, a second illumination laboratory with movable drop-down ceilings, the M2SEC research facility which houses cold and warm rooms with controllable room temperatures, and outside open real-time environments, etc. This puts a limitation on the calorimeter's dimensions to pass through doors and hallways (see Figures 6 – 8). The strictest limitation in a building are door frames. In the Engineering buildings, the narrowest and lowest doors have a width of 920 mm and a height of 2120 mm. The length of the calorimeter is not being affected. A second issue is the weight of the calorimeter. In order to be able to move it with one or two persons, the calorimeter will be mounted onto a set of wheels.

To test luminaires for their thermal performance, the calorimeter must provide an environment with parameters that can be easily controlled and influenced. To achieve this, the calorimeter will be highly insulated. This guarantees that only little heat is lost over the calorimeter enclosure.

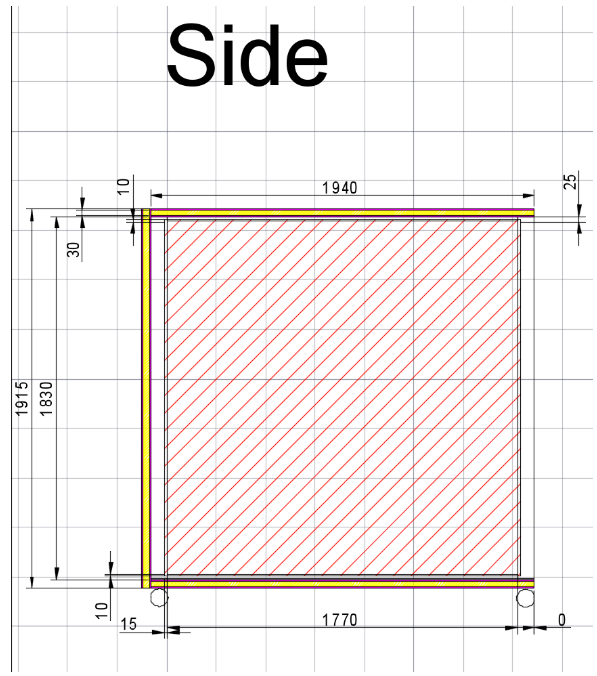


Figure 6: Drawing Side View Calorimeter

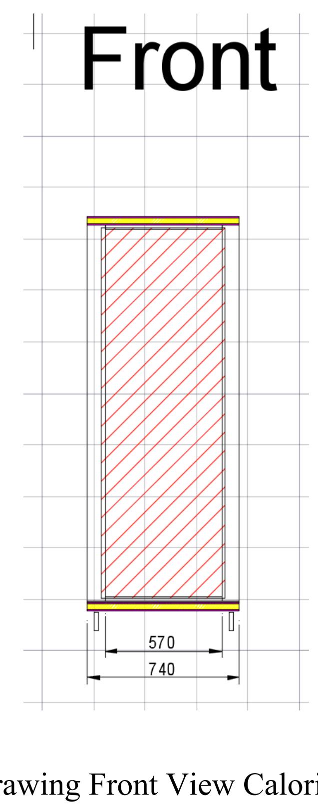


Figure 7: Drawing Front View Calorimeter

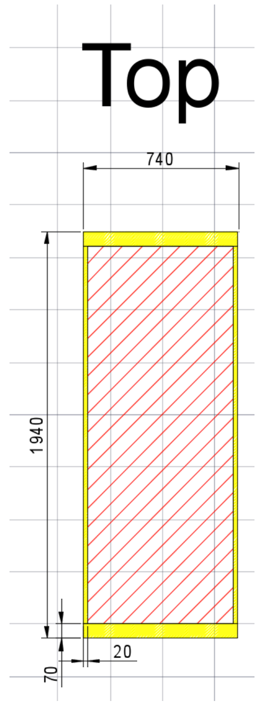


Figure 8: Drawing Top View Calorimeter

2.1 Wall construction

The walls of the calorimeter consist of five different layers. On the inside of the calorimeter, there is a layer of reflective aluminum foil to reduce radiant absorption and emission. The next layer are Vacuum Insulation panels with a depth of 30 mm. This layer is followed by a layer of 6 mm Aerogel insulation and the outside is finished off with a 5-mm layer of wooden panels. The calculated total wall depth will therefore be 43 mm. The walls on the long side have a dimension of 1800 mm by 1800 mm and on the short side of 600 mm by 1800 mm. The wall on one short side is a door to allow maintenance and therefore varies in construction.

To resemble an actual room, the calorimeter needs to maintain a relatively constant temperature inside. This is being achieved by air exchange. The air being added and removed from the calorimeter will be closely monitored, so the net amount of heat being removed from the calorimeter can be calculated (see Figure 9).

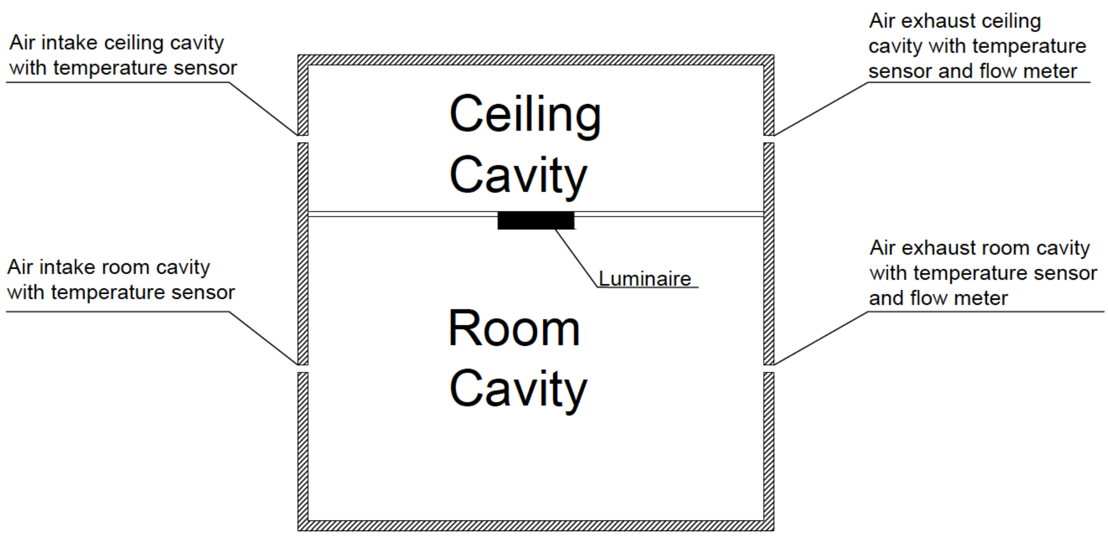


Figure 9: Calorimeter Air Intake and Exhaust Design

To allow air intake and removal, two holes with a diameter of 100 mm are added on both narrow sides of the calorimeter (narrow wall and door). One hole on each side is connecting the ceiling cavity, the other one is connecting the room cavity. Each hole is centered in its connected cavity. In this area, vacuum insulation panels cannot be used, as they lose their vacuum and thus their insulation capability if a hole is being cut into them. Therefore, the vacuum insulation panels are being substituted with XPS insulation (commonly referred to as “pink board”). The XPS insulation has a depth of one inch, which is only around 4 mm thinner than the vacuum panels and does not affect the construction much.

One of the key challenges is to hold the different layers together. Nails and screws can create thermal bridging effects, which would be negative for the project and therefore are not used excessively. Another issue is the risk of punching a hole into one of the vacuum insulation panels when installing a nail or screw. The calorimeter is supposed to be in use for decades. Therefore, glue is also not ideal as it can have aging effects, especially in environments with varying temperatures. To avoid all that, the different layers will be held together by the frame of the box. The wooden studs used will have grooves (15 mm depth for the vertical posts, 10 mm depth for the horizontal beams). These studs then hold together the walls of the box.

2.2 Floor and Ceiling

For the floor and ceiling, the construction differs from the wall construction to allow for easier construction. The ceiling has the same layers as the walls, but one layer of wood is added between the aluminum foil and the vacuum insulation panels to increase stability of the ceiling. The whole ceiling is put on top of the framework of the box instead of sitting in grooves like the walls. This is a step to further increase the stability of the calorimeter.

The whole calorimeter sits on a ground-framework with wheels. The insulated floor of the calorimeter is not directly connected to framework of the calorimeter, but rather sits on the ground-framework. With tight-fitting floor panels, it is still guaranteed, that there is no air leakage. The layers of the floor are different than ceiling and walls. Vacuum insulation panels are not being used, because the floor of the calorimeter needs to be structurally sound and this cannot be guaranteed with the vacuum insulation panels.

Therefore, two layers of XPS insulation are being used. In between those two layers, there is a layer of Aerogel. Again, the inside layer is aluminum foil.

2.3 Heat Transfer

The heat loss through the calorimeter's enclosure is a combination of all forms of heat transfer: convection, conduction and radiation. In the theoretical calculations for this model, only convection and conduction are being accounted for to simplify the calculation process. Due to the high reflectivity of the aluminum foul, the share lost through radiation is relatively low. Most of the heat being radiated by the luminaire would be reflected multiple times and ultimately heat up the air in the calorimeter.

To find the overall U-Value of the calorimeter, there are two pieces of information which need to be known:

- The heat transfer properties of the materials
- The size of the all areas with different heat transfer properties

2.3.1 Thermal properties of materials used:

Below are the heat transfer properties of the materials used in this project:

Aerogel:	k= 35 mW/(m*K) (Cabot, 2013)
Vacuum Insulation Panels (30 mm):	R= 4.285 m^2*K/W (Kingspan, 2014)
Wood board (5mm):	R= 0.044 m^2K/W (Architecture Toolbox, 2017)
XPS (30mm):	R= 0.88 m^2K/W
Whitewood stud:	R = 0.086 m^2*K/W*cm (AIDomes, 2017)

In addition, the heat transfer values from the air to the wall and from the wall to the air on the outside are important values (Schweizer-FN, 2017):

- Wall (outside): $\alpha_a = 0.12$ m^2K/W
- Wall (inside): $\alpha_i = 0.03$ m^2K/W
- Upward (outside): $\alpha_a = 0.12$ m^2K/W
- Upward (inside): $\alpha_i = 0.17$ m^2K/W
- Downward (outside): $\alpha_a = 0.17$ m^2K/W
- Downward (inside): $\alpha_i = 0.12$ m^2K/W

The air to wall heat transfer values used are the ones recommended to use for the thermal analysis of a building. The α- values (also known as R_{ia} and R_{oa}) depend on various factors and, if done in detail, need to be calculated as follows:

$$\alpha = Nu * \frac{\lambda}{d} \qquad \text{(Eq. 2.1)}$$

where:

α: surface resistance

λ: thermoconductivity of the fluid

d: wall roughness

Nu: f (Pr, Re)

k: thermal conductivity

$$Nu = C * Re^m * Pr^n \qquad \text{(Eq. 2.2)}$$

where:

Re: Reynolds number

Pr: Prandtl number

C, m, n are constants that can be found in the "VDI – Wärmeatlas" (VDI e.V., 2013).

The Reynolds number (Re) and the Prandtl number (Pr) themselves are a function of various characteristics of the fluid, the temperature and fluid speed. To get an exact α-value, this calculation would have to be done for every location in the box. This is only possible by computer simulation, therefore, the values given above have been used for this purpose.

2.3.2 Calculation of U-Values

To calculate the overall U-Value of the calorimeter, the easiest approach is to calculate the individual U-values for the different wall types.

- Wall section: R= 4.70 m^2K/W
- Wall section with XPS: R= 1.29 m^2K/W
- Wall section in 4 cm groove: R= 7.26 m^2K/W
- Wall section with XPS in 4 cm groove: R= 1.63 m^2K/W
- Ceiling: R= 4.70 m^2K/W
- Ceiling with stud: R = 5.34 m^2K/W
- Floor section: R = 1.69 m^2K/W
- Floor section (2" stud only): R = 0.43 m^2K/W
- Floor section (4" stud only): R = 0.86 m^2K/W
- Door Section with VIP: R= 4.65 m^2K/W
- Door section XPS: R= 0.948 m^2K/W

It is striking how much the R-values of the different wall constructions differ. Especially the Vacuum insulation panels with their very high R-Value compared to all other materials used have a huge impact on it. The low R-values of some parts may cause thermal bridging effects, but the construction does not allow another way.

To calculate the overall U-Value of the calorimeter, it is necessary to define the size of the areas with different wall constructions and the R-Value associated with them. In an excel sheet, the calculation of all areas and R-values was conducted for each individual part of the calorimeter (i.e., for each wall, ceiling, floor, door).

Each of the surfaces is being evaluated for one-dimensional heat transfer. It is assumed that the heat transfer in this direction is significantly larger than the heat transfer in the other two dimensions. Further assumed is a constant temperature within the calorimeter.

With the R- and α- values from above, the applicable areas from the CAD drawings and the following equation:

$$U = \frac{1}{\alpha_i + R_1 + R_2 + \cdots + R_n + \alpha_a} \quad \text{(Eq. 2.3)}$$

The overall U-Value of the calorimeter is listed in Table 1.

Table 1: Overall U-Value Calorimeter

Overall U-value		
Surface	Area	U-value
	m^2	W/m^2K
Long Side Walls	6.48	0.20
Short Side	1.08	0.21
Door	1.02	0.23
Ceiling	1.12	0.20
Floor	1.12	0.42
Overall U-Value	10.81	**0.23**

The goal for the calorimeter project was to construct a calorimeter that has an overall U-Value of 0.30 W/m^{2}K. This number was chosen by good judgement as a low value for heat loss to be able to make exact measurements with the calorimeter. The calculated heat loss of 0.23 W/m^{2}K is below the anticipated number of 0.30 W/m^{2}K. The actual calorimeter may have a varying heat loss below or close to the set maximum given other factors. Factors such as thermal bridging, imperfections in the construction, inaccurate R-Values of the materials and the simplification to one-dimensional heat transfer versus the three-dimensional heat transfer in reality have an effect on the and can alter the overall U-value. In addition, the α- values for the inside of the calorimeter are probably different from the literature values. This is due to the fact that we have moving air, a turbulent flow, inside the calorimeter. The heat transfer from air to another material strongly varies with the speed of the air. Therefore, while operating the calorimeter, it will have a varying U-Value as the air speed in the calorimeter will not always be the same.

2.3.3 Heat loss through air leakage

Usually, heat loss through air leakage (infiltration) is a significant contributor to the overall heat loss. In this case, though, the heat loss through air leakage does not need to be accounted for. In the way this calorimeter works, the air is pushed in by atmospheric pressure through two openings on one side of the calorimeter and warmer air is dragged out on the other side of the calorimeter. The fans and the air flow measurement are located on the exhaust side of the calorimeter. This way, all air that leaves the calorimeter is dragged through the exhaust. The inside of the calorimeter is under a slightly negative static pressure compared to the standard pressure. Air getting in through leaks is therefore not an issue, as this air can be assumed to be room temperature (temperature measured at the actual air intake), which will be measured and monitored throughout the actual experiments.

2.3.4 Illustration of potential heat loss

The U-Value illustrates the heat flux over a certain area with a defined temperature difference. To show how much heat the calorimeter loses (see Table 2), the heat loss has been calculated for steady state conditions with the following equation:

$$Q = U * A * (T_i - T_a) \qquad \text{(Eq. 2.4)}$$

where:

U: Overall U-Value of the Calorimeter

A: Surface Area of the Calorimeter

T_i: Air Temperature inside the Calorimeter

T_a: Air Temperature outside the Calorimeter

Table 2: Calorimeter Heat Loss Calculated

Sample Heat Loss Calculations	
Temperature Difference	Heat Loss
°C	W
1	2.5
2	4.9
3	7.4
4	9.8
5	12.3
10	24.6
15	36.9
20	49.2

The heat loss calculation for varying temperature differences between the inside and the outside of the calorimeter shows, as expected, a linear relation. It illustrates that it should be the goal while operating the calorimeter, to keep the temperature difference between the inside and outside of the calorimeter as low as possible. This will ensure that the unaccounted heat loss over the envelope of the calorimeter is as minimal as possible. For small luminaires, it is advisable to install multiple luminaires in the calorimeter while testing to have a higher heat gain.

3 Calorimeter Construction

The next step after designing the calorimeter was to construct it in house. At first, all CAD drawings needed to be reviewed to make sure the calorimeter could be constructed as planned. After this was done, a mass determination of all materials had to be done. Each individual part of wood was individually drawn in CAD.

The first step in the actual construction was cutting the wood according to the CAD drawings. The wood panels were cut using a table saw. The holes needed for air intake and exhaust were added using a 100-mm core drill. The 2” x 4” and the 4” x 4” studs used to build the frame work were cut to length by using a circular saw. The key challenge with the studs was creating a groove of 10 mm or 15 mm respectively. To cut the groove, a hand-held router was used. The depth of the groove was set by the router. To be able to also control the width of the groove, an auxiliary construction was built that limited the movement of the router. While working on the grooves with the router, one needs to be especially careful. The router is a very powerful tool and can easily cause damage to the studs that might later affect the stability of the calorimeter.

The idea was to build the framework, including the walls, in a first step and later add the ceiling and the floor as well as the wheels. The first part was the wall on the short side as shown in Figure 10. The 2”x4” studs on the bottom and two 4”x4” studs were screwed together to create a U-shape. The wood panel was put into the U-shape as the base (outer) layer. In the next step, the vacuum insulation panels and the XPS panels were added. The XPS parts were cut on the spot. This helped to decrease an issue that came up with the vacuum insulation panels. Those panels are ordered in predefined sizes, but the actual size of the panels does differ significantly in a lot of cases from the advertised size.

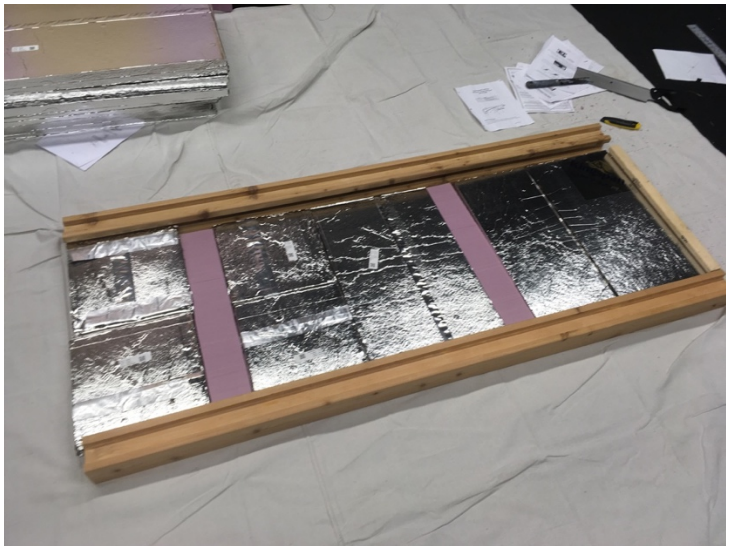
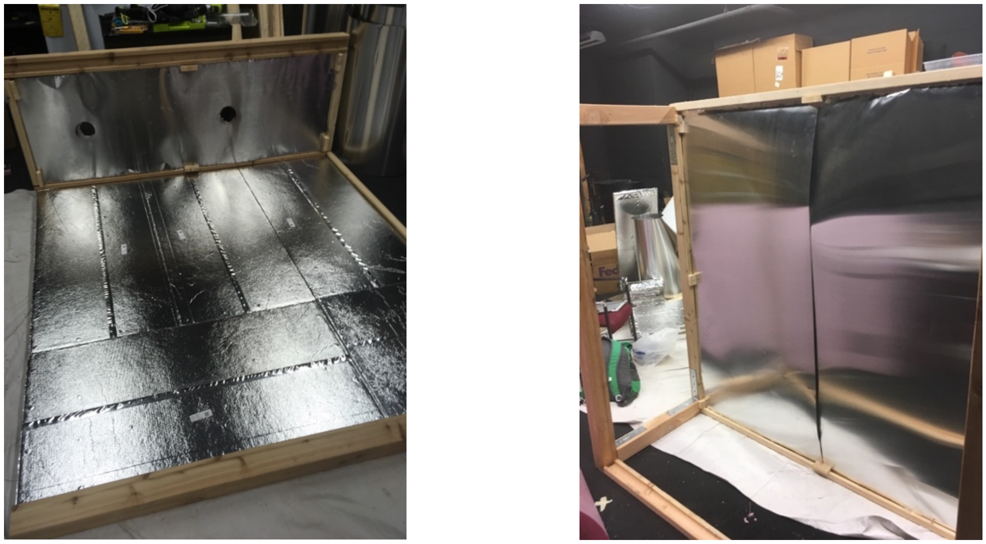


Figure 10: Construction Wall "narrow side"

In the following step, shown in Figures 11 and 12, one of the two long walls was added to the calorimeter. This was done in the same fashion as the short wall. The long wall does, however, not consist of one sheet of wood, but two that were aligned horizontally. This is due to the availability of the material. After finishing the second wall section, the now L-shaped construction was put on its feet.



(a) Second Wall during Construction (b) Frame lifted on its “feet”

Figure 11: Second Wall during and after Construction

Figure 12: Finished Wall - Outside View

Constructing the second long wall section was the step that followed (see Figure 13). The challenge at this point was that this wall section could not be put together on the floor, but had to be done standing up. The most difficult parts were adding the wallboard and applying the aluminum foil. Another issue that came up with this side wall was fitting in all the Vacuum Insulation panels. Due to their differing sizes, one vacuum insulation panel did not fit into the wall. Therefore, it was substituted with an XPS panel that was custom fitted for the gap. During the commissioning, the position of this panel might be visible on thermal images as a warmer part of the wall. To finish the framework of the calorimeter, the two long walls were then connected with two 4”x4” studs on the door side to make a cube out of the U-shape.

(a) Wall Construction (b) Adding Vacuum Insulation

Figure 13: Wall Construction

With the walls being completed, the calorimeter needed a roof. The roof was not preassembled but rather built on top of the framework. The first layer of the of the ceiling was a sheet of wood with the dimensions of the framework. This was topped with a layer of Vacuum insulation panels and a layer of Aerogel and then again finished with a second layer of wood-sheet. On both short ends, a 2”x4” stud was added and connected to the framework to hold the roof together. The spare room on both sides was filled with XPS which is held in place by heavy-duty tape. Lastly, the aluminum foil was applied from the bottom and fixed with screws. By using short screws, the risk of injuring one vacuum panels was eliminated.

As mentioned earlier, the mobility of the calorimeter is a key aspect of the construction. Therefore, this needed to be accounted for when constructing the bottom part of the calorimeter shown in Figure 14. A second framework was built with two parallel 2”x4” stud with the same length as the length of the framework that are connected by 5 short studs. Five wheels, one at each corner and one in the center of the frame, were added. Now, the calorimeter chamber needed to be put on the frame. However, this turned out to be a challenge as the chamber is relatively heavy. With the help of five people, the chamber was lifted onto the frame. Then, the floor insulation could be applied. Two pieces of XPS insulation were cut to fit into the frame on the bottom. They were put in with a layer of Aerogel in between and then topped with a sheet of aluminum.

(a) Supporting Floor Construction

(b) Floor Construction

(c) Insulated Floor

Figure 14: Floor Construction

The door is again a sandwich-construction. The inner and outer layer of the door are wood panels with the two 100 mm holes for air intake. These doors are mounted on a square frame of 2”x4” studs. The square is the filled with insulation material. Again, on the inside, there is a sheet of aluminum foil screwed onto the door. The main challenge regarding the door was how to mount it. The door needs to be very tight fitting, but also easily removable. Therefore, a seating for the door was created with two metal L-profiles. The door is put onto these L-profiles. To fix the door, three ratchet straps are being used. The ratchet straps are mounted around the calorimeter and are then being fixed on the side of the door. To make the connection between the box’s frame and the door as air tight as possible, an elastomeric gasket (commonly used in cars or window frames) was applied on the box to seal the gap between door and box.

During the construction process, some gaps between the different parts of the calorimeter showed up. To fill large gaps, expanding foam insulation was used. Small gaps were filled with caulk.

The outside surface of the calorimeter is painted in black as illustrated in Figure 15. This has been done, so the calorimeter can be located in KU’s dark room, a room with almost all surfaces painted in black.

(a) During the painting (b) Painted Calorimeter

Figure 15: Calorimeter Painting

3.1 Fan Installation

To move air through the calorimeter, fans are being needed. Due to the decision that the fans are supposed to suck air through the calorimeter instead of blowing, the fans have to be installed on the exhaust side of the calorimeter. By installing the fans on the exhaust side of the calorimeter, heat generated by the fans will also not influence the measurement.

In order to not further increase the size of the calorimeter and keep it relatively mobile, the fans are mounted on a separate utility cart. On the utility cart, the fans are being fixed with tape. This may not be the ideal way to mount them, but due to the unusual application, this is the only way that worked at this point. At a later time, there might be room for improvement here. The fans are then connected to the exhaust side of the calorimeter with a flexible duct (diameter: 100 mm). The duct is also fixed to the utility cart to improve stability.

4 Equipment

This chapter introduces all the equipment used for the calorimeter itself, as well as the technology used during the commissioning process to guarantee a proper functionality of the equipment.

4.1 Fans

As explained in the previous chapter, fans are being utilized to generate air flow through the chambers of the calorimeter. For choosing the right fans, there were two major factors that influenced the decision:

- The fan needs to be able to operate at the right air flow rate with the correct static air pressure. For the calorimeter application, this means that the fan needs to be able to operate at a very low air flow rate to test LEDs with a low power, but also at a high air flow rate, so LEDs with a power of up to about 500W can be tested without reaching too high temperatures in the calorimeter.
- The fan speed needs to be adjustable, to allow for the different air flow rates mentioned above. The speed adjustment should be easy without any tools needed.
- The air exhaust port is 100 mm. Therefore, the fan should ideally be of four-inch diameter to make installation easier.

The Calorimeter is a rather unusual application and finding a fan suitable for this application proved to me more difficult than expected. After some searching, a fan was found that meets all criteria mentioned above.

The Fantech FG4XL EC Centrifugal Inline Fan was selected for this application. The 4-inch diameter fan which runs on 120 V AC works at an air flow rate between 0 and 85 l/s and has a maximum static pressure of around 500 Pa which is more than required for this application (Fantech, 2017).

To be able to control the speed of the fans, two MTP10 potentiometers from Fantech were also acquired. These potentiometers allow infinitely variable selection of the air flow rate.

4.2 Air Flow

To calculate the heat being released by the luminaires tested in the calorimeter, the air flow in and out of the calorimeter needs to be measured. For the air flow measurement, the following aspects are important:

- The measurement needs to be accurate to allow the calorimeter to work.
- The measuring interval needs to be short, so abrupt changes in air flow are accounted for.
- The equipment used should be easy to operate. This means that once a measurement is started, it only needs monitoring and not constant attendance.

To measure the air flow rate (volumetric flow rate or air speed) a tool called anemometer is being used. There are different types of anemometer that are being used in the field of building sciences:

- Vane Anemometer
- Hot-wire anemometer

- Laser-Doppler anemometer
- Pressure tube anemometer

Laser-Doppler anemometer are a highly sophisticated, extremely accurate and expensive tool to measure air flow. They are exceeding the expectations for our application. Hot-wire anemometer are very accurate and not too expensive, but they have one disadvantage that disqualifies them. They only measure air speed at one point. In a tube, the air speed between the center and the periphery differ. To get an accurate reading with a hot-wire anemometer, a grid measurement would be required. For a pressure anemometer, one needs a piece of tube with no leakage to measure the dynamic pressure. Such a piece does not exist at the calorimeter. Therefore, a vane anemometer has been selected.

The products chosen, shown in Figure 16, are produced by testo, a German company that is a world leader in measurement instrumentation. As a data logger, the testo 480 was selected. Connected to the data logger are 2 fan probes (anemometers) with a diameter of 100 mm that can measure the air speed and temperature. The fan probes can measure air speed between 0.1 and 15 m/s (2.83 – 424 m^3/h). The accuracy is give as +/- 0.1 m/s plus 1.5% of the measured value. For an air speed of 2 m/s, the actual air speed could be in the interval 1.87 m/s to 2.13 m/s. With the air speed, the data logger is capable of computing the volumetric flow rate. The data logger can be connected and operated with a software for PC that allows for advanced controls and an output of data into excel. The data logger can measure in intervals of as little as one second. Currently two fan probes are connected to the data logger and the logger has the capability of handling one additional probe (Testo, 2017) .

(a) Testo 480 (Testo, 2017)

(b) Fan measurement probe (Testo, 2017)

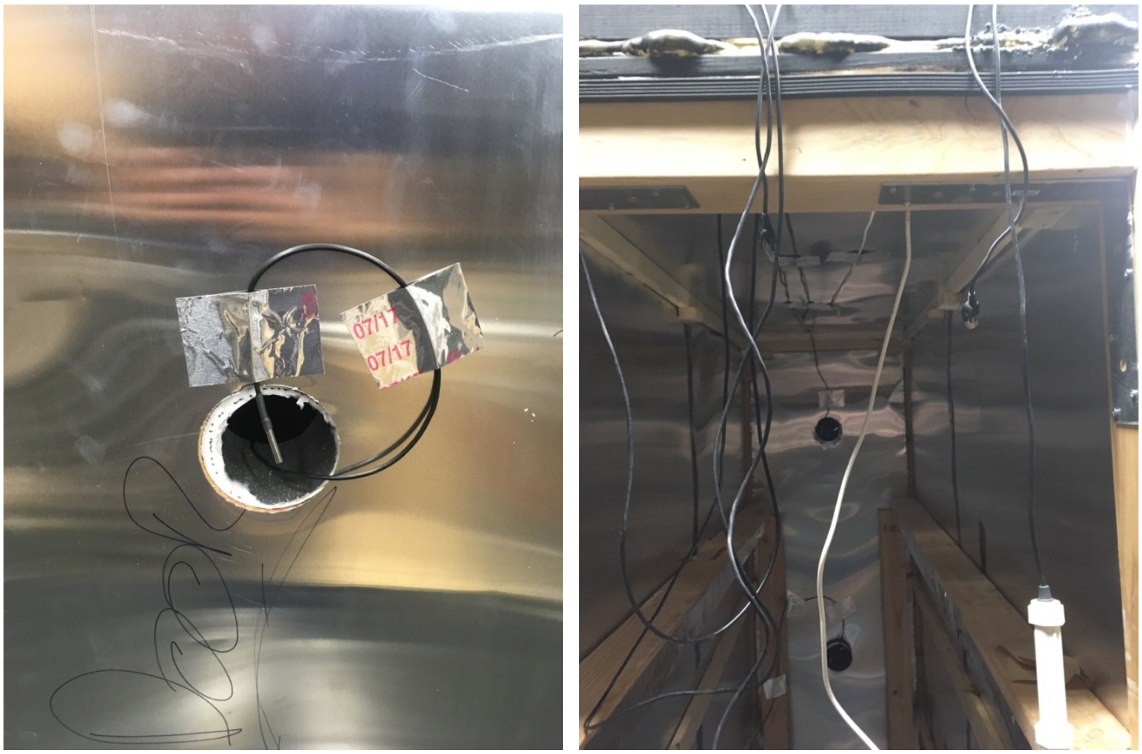
Figure 16: Air-Flow Measurement Equipment

4.3 Temperature Control

To analyze the heat released in the calorimeter, temperature measurements at different points in the calorimeter are necessary. In total, six temperature sensors and two humidity sensors are currently mounted in the calorimeter, with the option of mounting additional sensors if needed (see Figure 17).

One sensor is mounted at each of the air intakes as well as at the air exhausts in both the ceiling and the room cavity. In addition, there is one temperature sensor in the center of the ceiling cavity both in the ceiling cavity and the floor cavity close to the heat source

(LED) in the calorimeter. At these positions, there is also a humidity sensor mounted. The humidity sensors are required to compute the mass flow of air.

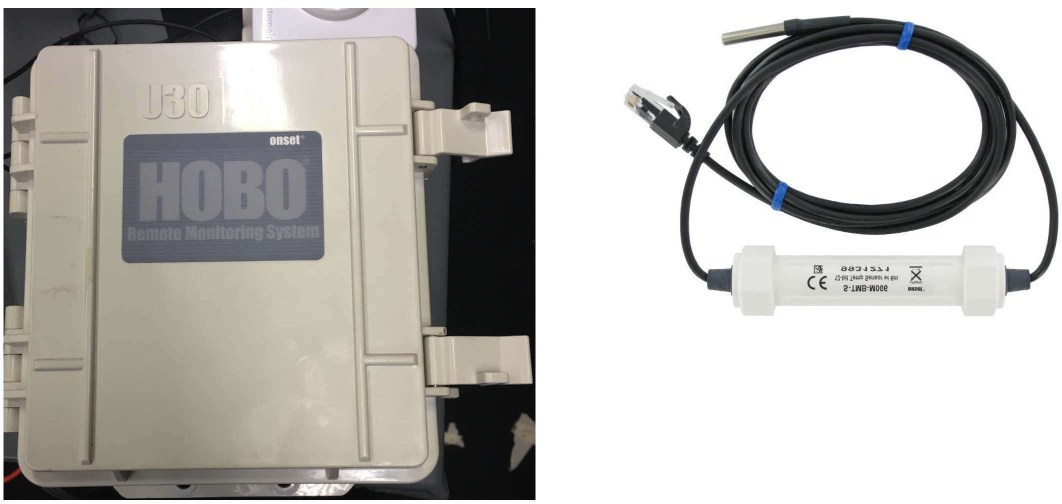


(a) Temperature Sensor - Exhaust (b) Temperature Sensors installed

Figure 17: Temperature Sensors

The sensors are S-TMB-M006 from the company onset (see Figure 18). The initial accuracy of the sensors is +/- 0.2 °C and the sensors have a drift of 0.1 °C per year. Due to the drift, changing or calibrating the sensors every few years is advisable. At an air speed of 1 m/s, the response time to 90% is less than 3 minutes. Since the "warm-up phase" of the calorimeter, which will be explained in section 5.3.2, is more than one hour, the response curve to air flow should not be an issue (ONSET, 2017). The temperature sensors are Resistance Thermometers (RTD), which offer a higher accuracy and a lower drift than other common temperature sensors.

The sensors are connected to a HOBO U30 data logger which can handle up to 10 sensors. The data logger is connected to a computer and transfers the data into the software HoboWare. HoboWare allows for output of the data into Excel.



(a) Hobo U30 Data logger (b) Temperature Senor (ONSET, 2017)

Figure 18: Temperature Measurement Equipment

5 Commissioning

A laboratory test stand can only be of use, if the measurement results are proven to be accurate with a low margin of error. To meet this criterion, the calorimeter needs to undergo a commissioning process. This means, the heat measured by the calorimeter needs to be compared to a test source with a known, defined heat output.

5.1 Theory of heat calculation

The calorimeter uses the enthalpy difference between the air that enters and exits the calorimeter and the mass flow to calculate the heat released in the calorimeter.

$$\dot{Q}_{tot} = \dot{Q}_{ceiling} + \dot{Q}_{room} \qquad \text{(Eq. 5.1)}$$

Where:

Q_{tot}: Total heat gain in the calorimeter

$Q_{Ceiling}$: Heat gain in the ceiling cavity

Q_{Room}: Heat Gain in the room cavity

For each of the two chambers, the heat gain is calculated as follows:

$$\dot{Q}_{Cavity} = (h_{out} - h_{in}) * \dot{m} \qquad \text{(Eq. 5.2)}$$

Where:

Q_{Cavity}: Heat gain in one of the cavities (kW)

h_{out}: Specific enthalpy of the air leaving the calorimeter (kJ/kg)

h_{in}: Specific enthalpy of the air entering the calorimeter (kJ/kg)

$\dot{m}$: Mass flow of air (kg/s)

The specific enthalpy of air is a function of both the temperature and the absolute humidity of the air. In the laboratory, the air will always be unsaturated. Therefore, the specific enthalpy can be calculated with (Cerbe & Wilhelms, 2011):

$$h = c_{pL} * t + x * \left(c_{pD} * t + r_D\right) \quad \text{(Eq. 5.3)}$$

Where:

c_{pL}: Specific heat capacity of air – 1.004 kJ/(kg*K)

c_{pD}: Specific heat capacity of steam – 1.86 kJ/(kg*K)

t: Air temperature (K)

r_D: Evaporation heat at 273.15K (0°C) – 2500 kJ/kg

x: Absolute humidity (kg_{Water} / $kg_{Dry\ Air}$)

The calorimeter records temperature and relative humidity data, but does not measure the absolute humidity which therefore needs to be calculated (Cerbe & Wilhelms, 2011):

$$x = 0.622 * \frac{p_S(t)}{\frac{p}{\varphi} - p_S(t)} \quad \text{(Eq. 5.4)}$$

Where:

p_s (t): Water vapor saturation pressure at air temperature (Pa)

p: Barometric pressure (Pa)

φ: Relative humidty (Range: 0-1, not in %)

The calorimeter, as mentioned before, also monitors the volumetric flow rate of air. With the volumetric flow rate, the temperature and the absolute humidity of the air, the mass flow of air can be calculated (Cerbe & Wilhelms, 2011):

$$\dot{m} = \frac{\dot{V} * p}{R_D * t} * \frac{1}{(0.622 + x)} \quad \text{(Eq. 5.5)}$$

Where:

$\dot{V}$: Volumetric flow rate of air (m^3/s)

p: Barometric pressure (Pa)

R_D: Gas constant water vapor – 461 J/(kg*K)

t: Air temperature (K)

x: Absolute humidity (kg_{Water} / $kg_{Dry\ Air}$)

$\dot{m}$: Mass flow of air (kg/s)

5.2 Commissioning Process

The calorimeter has been commissioned through a set of measurements with different parameters. The goal thereby is to find out whether the heat that is being released by a heat source (luminaire) in the calorimeter will also be accurately detected by the temperature sensors and anemometers installed in the calorimeter.

To test this, a heat source with a known heat output is used. In the center of the calorimeter, between the two cavities, a cartridge heater is installed. The heater is powered by a 60 V DC power source which allows to set the heat output of the cartridge heater in a range from 0-114 W. This range is also the range of heat flux for standard LED luminaires used in indoor settings. The heat output by the cartridge heater was given by the DC source which shows how high the energy input is.

The air flow through the calorimeter is a second variable in the calorimeter. It will have an influence on the temperatures inside and on the exhaust side of the calorimeter.

To analyze the impact of both the power output of the heat source and the air flow rate, three sets of measurements will be conducted:

- In the first set of measurements, the air flow rate is constant and set at an air speed of 2 m/s for each of the two fans. The variable in this case is the power of the heat source. Three measurements are being made: one at 114 W (max. wattage), one at 75 W and one at 50 W.
- In the second set of measurements, the power of the heat source is set at 75 W and the air flow rate is varied. Tested air velocities are: 2 m/s and 3 m/s
- The third measurement will be made with air velocities of 1 m/s. The power input will be 10, 25 and 50 W.

These measurements allow us to analyze the impact of both variables on the recorded data of the calorimeter. The commissioning measurements run for several hours to make sure that a steady state is reached.

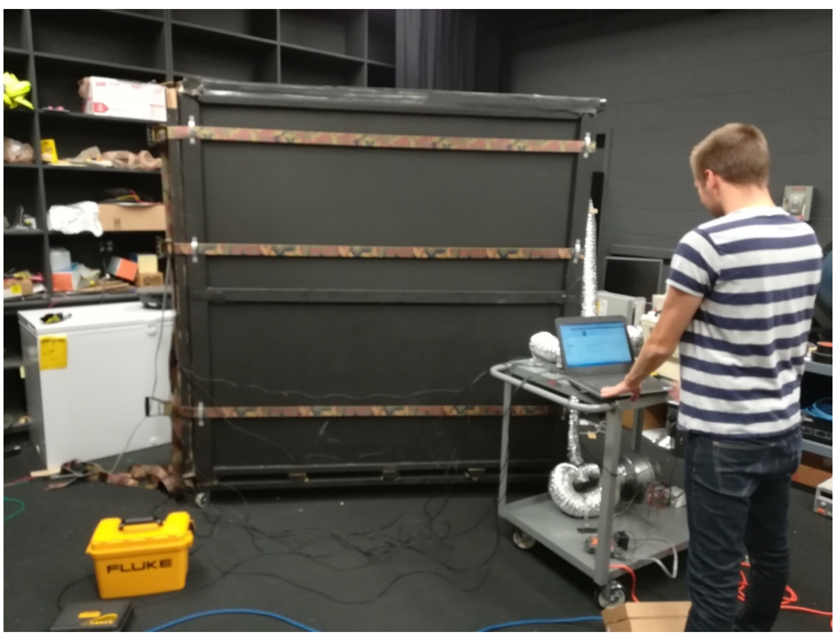


Figure 19: Calorimeter during Commissioning

5.3 Results

In this section, the results of the commissioning process will be presented and evaluated. There are three main aspects that will be looked at: thermal images of the calorimeter to find areas with high heat loss rates, the temperature development in the calorimeter and the measured heat compared to the power input.

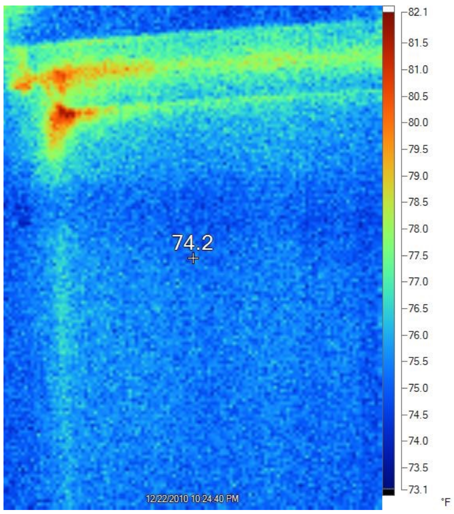
5.3.1 Thermal images

During the commissioning process, thermal images of the envelope of the calorimeter were made to detect areas with high heat loss rates. Thermal images are photos in which the color does not represent the color of the object, but the surface temperature of the object. Colder areas are blue, hotter areas are red in thermal images. A scale on the side of the image always indicates which color represents which temperature as this varies depending on the surface temperatures in the image. For the thermal images, a Fluke Ti100 thermal camera was used.

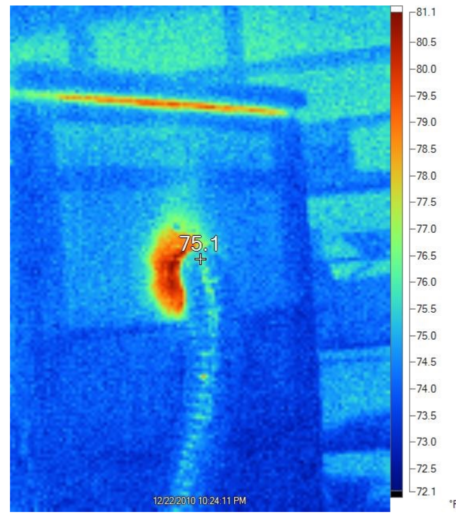
Figure 20: Fluke Ti 100 Thermal Camera

The thermal images of the calorimeter show good results. Most of the surface area shows a uniform temperature distribution. Only the air exhausts have higher temperatures which was expected and is not an issue, as warm air is being moved there and the heat loss it outside of the measurement area.

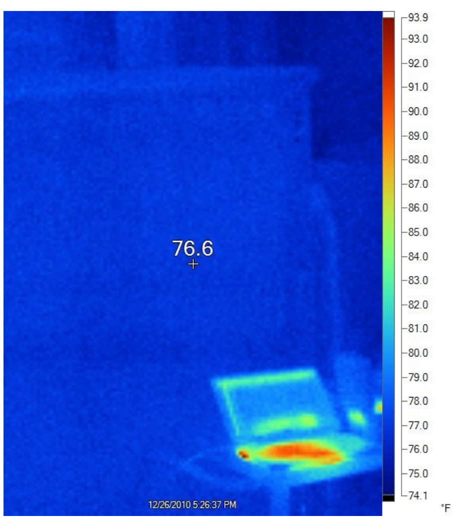
Looking at the calorimeter's exhaust side, an area with higher heat loss can, however, be detected. The roof on this side seems to be a little warmer than the rest of the side (see Figure 21 b). Due to the way the calorimeter is constructed, this leak does not allow a for a lot of optimization. On one of the long sides, the top left corner appears to be a small source of heat loss (see Figure 21 a). In this corner, the Vacuum panels have probably moved a bit and created a gap. The other warm part that can be seen in some of the images is the computer logging data. This was used to generate a higher contrast in the pictures in order to increase visibility.



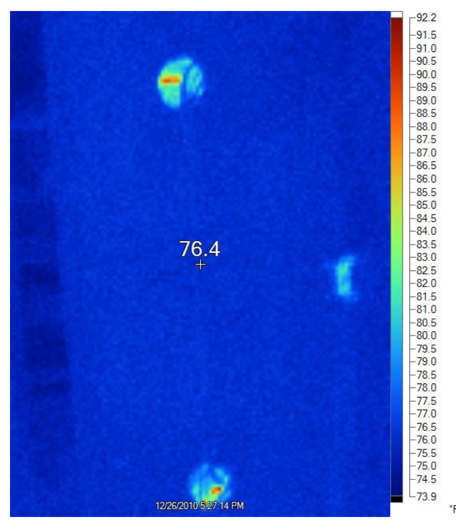
(a) Detail: Top Corner



(b) Exhaust Side



(c) Calorimeter during Commissioning



(d) Air Intake

Figure 21: Thermal Images

5.3.2 Temperature Development

This section will illustrate the temperature changes of the different measurement points in the calorimeter during the measurement process. Six lines will illustrate the temperature at both air intakes, the temperature in the center of the ceiling and room cavities and the temperature at the ceiling and room air exhaust. The results are sorted from the lowest to the highest energy input.

Figure 22: Temperature Curve 10 W - 1 m/s

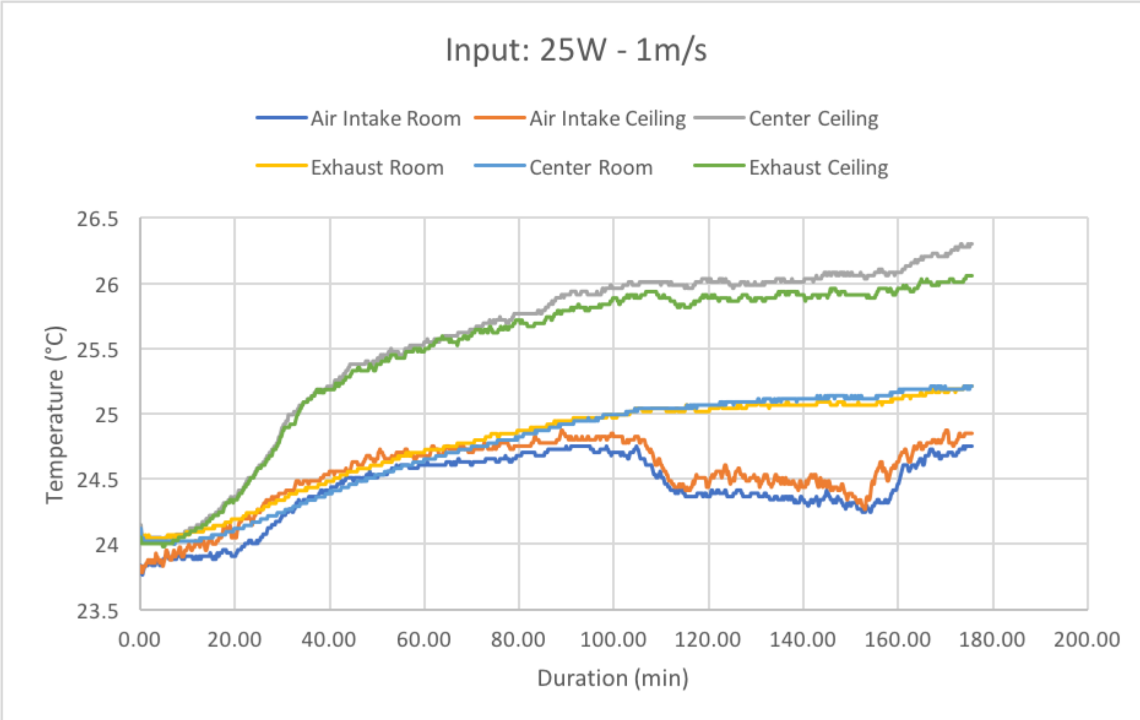


Figure 23: Temperature Curve 25 W - 1 m/s

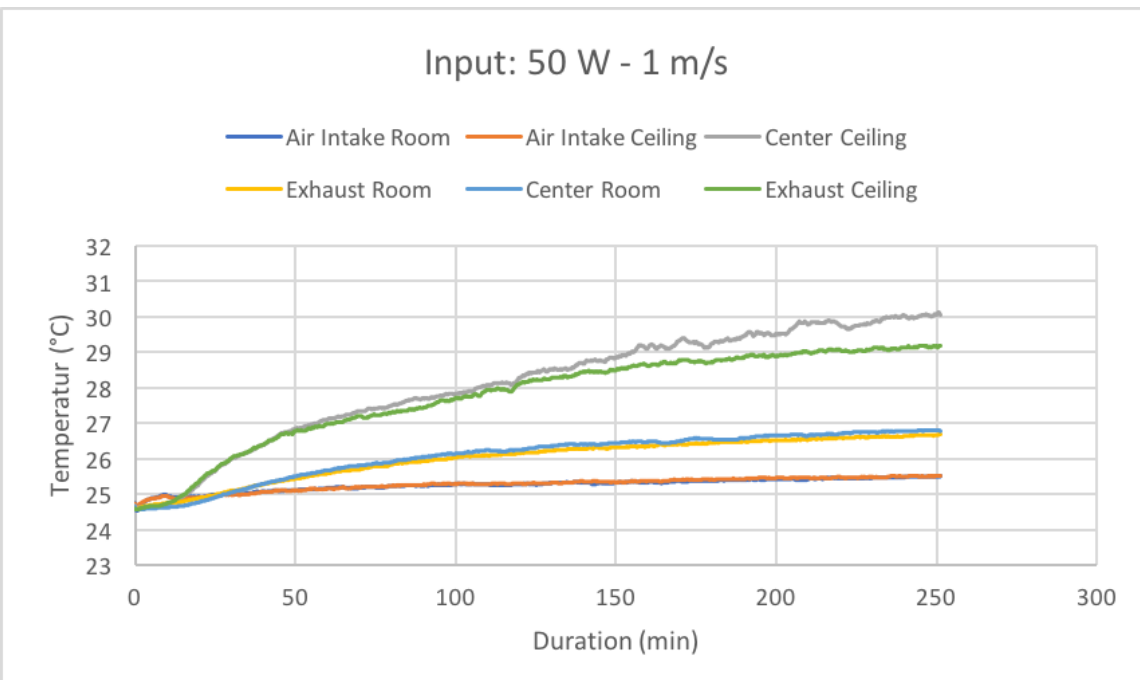


Figure 24: Temperature Curve 50 W - 1 m/s

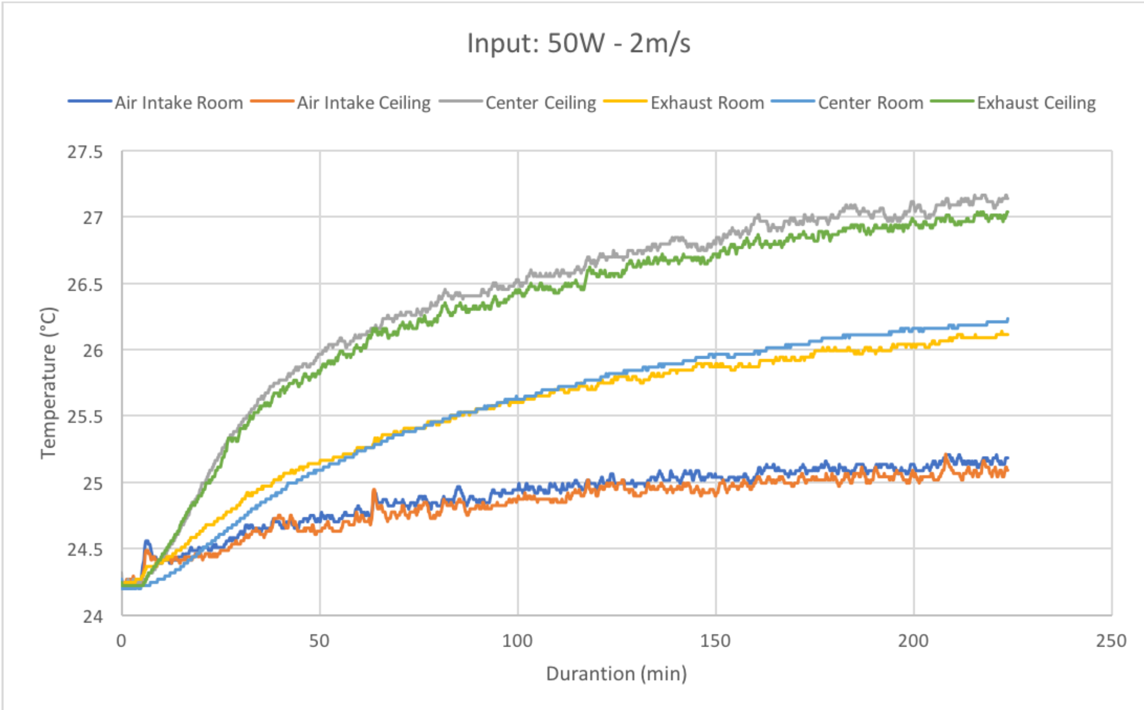


Figure 25: Temperature Curve 50 W - 2 m/s

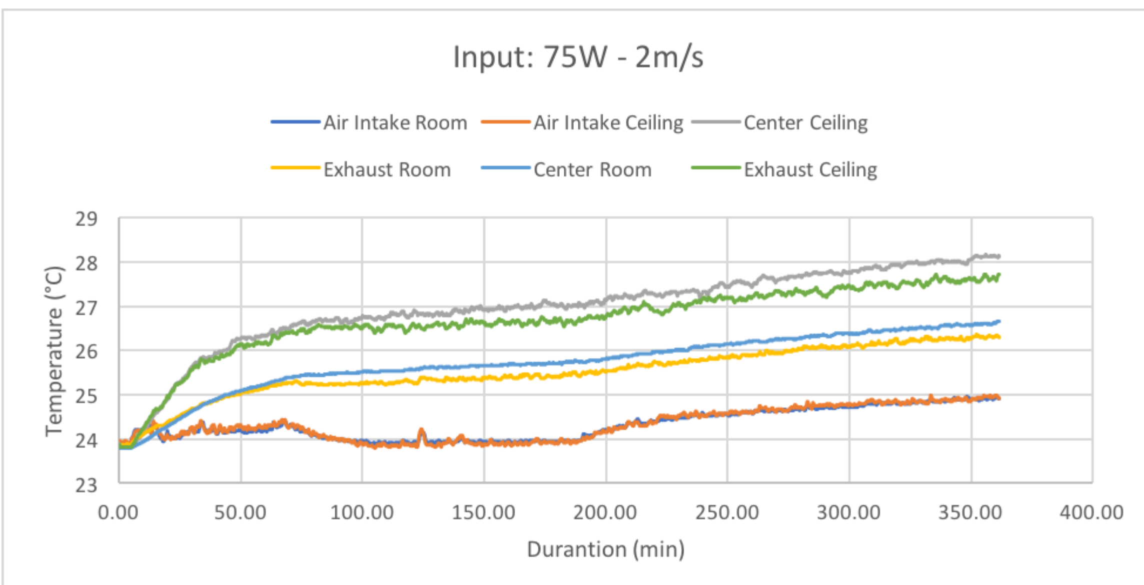


Figure 26: Temperature Curve 75 W - 2 m/s

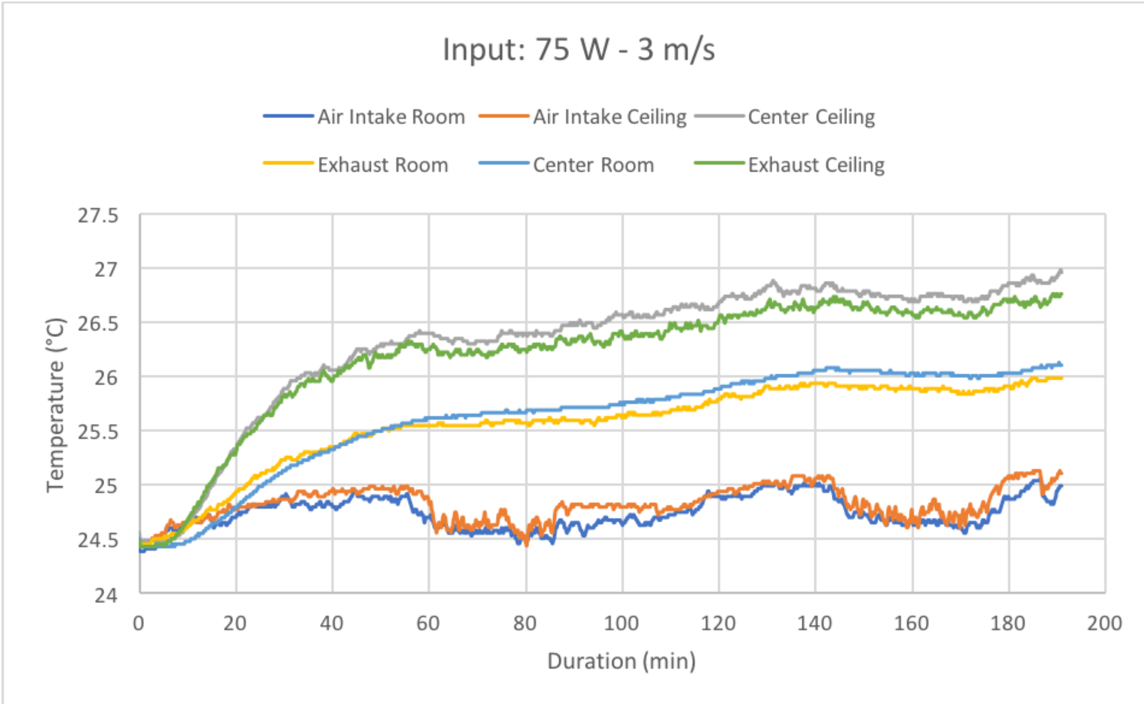


Figure 27: Temperature Curve 75 W - 3 m/s

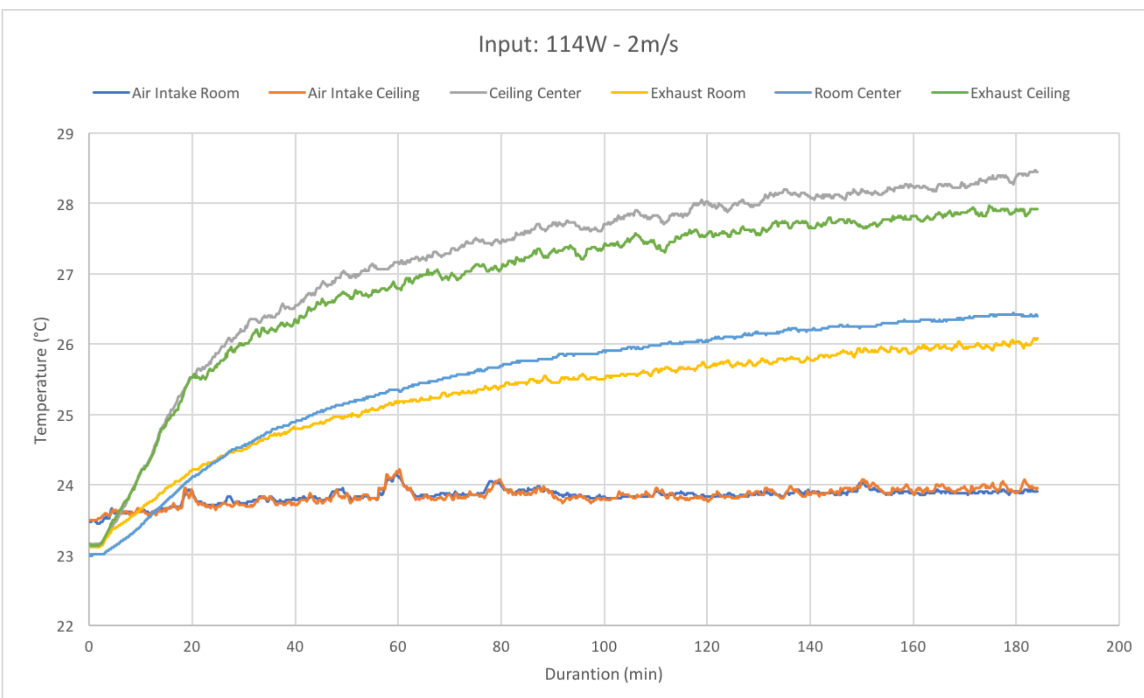


Figure 28: Temperature Curve 114 W - 2 m/s

There are various aspects that are interesting in the calorimeter temperature curves. First of all, the 114 W curve (Figure 28) is probably the curve that represents the "ideal" case. The temperatures at both air intakes remain constant throughout the measurement, while the temperatures at the other four sensors increase. The response curve that the sensors in the center of the calorimeter and at the exhaust side are showing is a typical response curve for such a scenario. At first, the temperature rises quickly, because the temperature difference between the surface of the cartridge heater and the air in the calorimeter is high. As the temperature in the calorimeter is slowly rising, the temperature difference between the surface of the cartridge heater and the air decreases. Therefore, the heat transfer rate between the surface and the air decreases, which leads to a slower rise of the temperature in the calorimeter and at the exhaust. This curve is ultimately approaching a balance point. At this point, the energy input through the cartridge heater will also be the heat loss through the air being dragged through the calorimeter and the heat loss through the surface of the calorimeter. This point is being reached at a duration of roughly 170 minutes as the temperature at this point is barely rising anymore.

The measurements with a 50 W input and 2 m/s air speed (Figure 25) shows a very similar result. The balance point is also reached after about 170 minutes and the temperature curves have a very similar shape with one distinction. The temperature of the room is rising throughout the experiment. Therefore, at the balance point, the temperatures are not constant, but rather rising at the same pace. The rise of the temperatures at the air intake is not related to the experiment itself, but rather caused by heat gain in the room. It does not influence the measurements, as calculations only use temperature differences and not absolute temperatures.

The measurement made with 50W of power input and an air speed reduced to 1 m/s (Figure 24) showed a very similar result. The shape of the temperature curves is a little flatter, which means that the temperature in the calorimeter is rising at a more constant pace. The balance point temperatures in the calorimeter are higher with the reduced air speed, since this means less heat is being removed from the calorimeter. Therefore, the balance point is being reached after a longer duration.

The two measurements at 75W (Figures 26 and 27), with an air speed of 2 m/s and 3 m/s, show a similar pattern. The maximum temperature at the lower air speed is again higher and the duration until the balance point is reached is longer. The shape of the curves also shows the same differences as at the 50W measurement.

At the 25 W measurement with an air speed of 1m/s (Figure 23), the temperature curves for the center of the room cavity and the exhaust of the room cavity show the same shapes as in the other measurements made. The ceiling cavity center and the exhaust temperature of the ceiling cavity are more unsteady in their rise. One of the reasons for this may be the temperature at the air intakes (room temperature). The temperature does not show the same consistency that it has shown in the other measurements. The temperature rises at first and then suddenly drops again which may be due to air conditioning.

The 10 W measurement (Figure 22) shows a very different temperature development than all other measurements. One thing that can be seen in at the start of the measurement is the response time of the sensors. Due to the moving air, the sensors need a few minutes until their measurement is accurate. The temperature curves for all measurement point show a different shape. The rise in temperature is minimal. They do not follow the same pattern as the temperature curves in the other measurements. This is a hint that this has been an unsuccessful measurement.

All curve show noise. Due to the fact that the even the curves at the air intake show this noise, the reason for the noise is probably small changes in air temperature in the room. Another reason could be the turbulent flow and uneven temperature distribution in the calorimeter.

5.3.3 Measured heat

The following tables show the calculated heat output, the energy input and all measured and calculated values used to compute the heat output. The measured values were taken at the end of each measurement when the balance point had been reached. To eliminate measurement values, an average of the 60 measurements in a 10-minute span was used. The measurements are again ordered by input power. The

Table 3: Excel Calculation Sheet

Calorimeter Data Analysis		
Energy Input	**10.1**	W
Ceiling		
Temperature Air Intake	24.81	°C
Temperature Exhaust	25.44	°C
Air Speed	1	m/s
Absolute Humidity	0.0048	kg Water / kg dry Air
Volume Flow	0.00785	m^3/s
Mass Flow	0.00921894	kg/s
Enthalpy Difference	0.63814464	kJ/kg
Thermal Output	**5.9**	W
Room		
Temperature Air Intake	24.94	°C
Temperature Exhaust	25.06	°C
Air Speed	0.99	m/s
Absolute Humidity	0.0048	kg Water / kg dry Air
Volume Flow	0.0077715	m^3/s
Mass Flow	0.00913838	kg/s
Enthalpy Difference	0.12155136	kJ/kg
Thermal Output	**1.1**	W
Total Thermal Output	**7.0**	W
Differencce Input - Output	**-30.8**	%
Ratio Ceiling/Room	**5.3**	

Table 4: Thermal Output Calculations

Calorimeter Commsissioning								
	Unit	10 W - 1m/s	25 W - 1m/s	50 W - 1 m/s	50 W - 2 m/s	75 W - 2 m/s	75 W - 3 m/s	114 W - 2m/s
Energy Input	W	10.1	25.2	49.8	50.2	74.2	74.2	114.2
Ceiling								
Temperature Air Intake	°C	24.81	24.72	25.51	25.08	24.89	24.65	23.95
Temperature Exhaust	°C	25.44	25.98	29.11	26.98	27.59	26.59	27.87
Air Speed	m/s	1	1.07	0.97	2.08	2.01	3.03	2.07
Absolute Humidity	kg Water / kg dry Air	0.0048	0.0055	0.00606	0.0075	0.0065	0.0055	0.0056
Volume Flow	m^3/s	0.0079	0.0084	0.0076	0.0163	0.0158	0.0238	0.0162
Mass Flow	kg/s	0.009219	0.009835	0.008816	0.018995	0.018348	0.027795	0.018905
Enthalpy Difference	kJ/kg	0.638	1.278	3.655	1.934	2.743	1.968	3.977
Thermal Output	W	**5.9**	**12.6**	**32.2**	**36.7**	**50.3**	**54.7**	**75.2**
Room								
Temperature Air Intake	°C	24.94	24.61	25.49	25.16	24.9	24.63	23.89
Temperature Exhaust	°C	25.06	25.04	26.64	26.18	26.27	25.86	25.96
Air Speed	m/s	0.99	1.03	0.99	1.99	2.06	3.07	1.98
Absolute Humidity	kg Water / kg dry Air	0.0048	0.0055	0.00606	0.0075	0.0065	0.0055	0.0056
Volume Flow	m^3/s	0.0078	0.0081	0.0078	0.0156	0.0162	0.0241	0.0155
Mass Flow	kg/s	0.009138	0.009498	0.009072	0.018222	0.018887	0.028231	0.018199
Enthalpy Difference	kJ/kg	0.122	0.436	1.168	1.038	1.392	1.248	2.100
Thermal Output	W	1.1	4.1	10.6	18.9	26.3	35.2	38.2
Total Thermal Output	W	**7.0**	**16.7**	**42.8**	**55.7**	**76.6**	**89.9**	**113.4**
Differencce Input - Output	%	-30.8	-33.7	-14.0	10.9	3.3	21.2	-0.7
Ratio Ceiling/Room		5.3	3.0	3.0	1.9	1.9	1.6	2.0

With table 4 showing the energy input, the energy output and the difference between those to values, it is easy to evaluate how accurate the calorimeter measurement can be.

For high input energy (114 W and 75 W) and an air speed of 2 m/s, the difference between the heat input and the measured heat output is very low. In this area, errors of less than 5% were achieved. At the 75 W measurement, it is striking that the error sharply increases with a higher air speed in the calorimeter.

The 50 W measurement shows a very different effect. In this case, the measurement at 2 m/s air speed shows a higher accuracy than the one at a reduced air speed of 1 m/s. The measurement at 2 m/s is within 11% of the energy input, which is still an acceptable margin of error. The 1 m/s – measurement shows a higher error of almost 14%.

The measurements with an input of 10 W and 25 W both show an error 30.8% and 33.7% respectively. This cannot be considered an accurate measurement anymore.

6 Conclusions and Recommendations

The goal of this project was to develop a calorimeter which resembles an actual room application, allows for accurate evaluation of the thermal evaluation of luminaires in general and LEDs in specific and allows all forms of luminaire mounting.

This goal has partially been met. The calorimeter that has been constructed has indeed a very low U-Value. According to calculations, the U-Value is 0.23 $W/m^2 K$ and the testing, especially the thermal images have shown that there is not a lot of heat loss over the envelope of the calorimeter. The commissioning process has also shown that measurement with a thermal input of 50 W or greater at a reasonable airspeed generates results with an error of 0.7% (114 W) to 11% (50 W) that can be used for research application in the field of the built environment.

The calorimeter is not directly affected by the surrounding temperature. At the start of a measurement, the temperature inside the box and outside are the same and the temperature difference only develops during the measurement. This means that e.g., an LED luminaire for residential applications can be assessed at room temperature and a streetlight can be assessed at the temperature level that it faces during application. A constant surrounding temperature during the measurement is advisable, however. Looking at the temperature graphs during the measurement shows, that a changing surrounding temperature (input temperature) also affects the temperature inside the calorimeter much if near the chamber's temperature and therefore the measurement. With a changing surrounding temperature, the balance point is changing. In addition, the calorimeter needs some time to adjust to a new balance point which can lead to inaccuracy in the measurement. The Lighting Research Lab's Dark Room has shown a slightly, constantly rising temperature during most measurements. The changes in temperature are not deemed significant enough to influence the measurement. Though, a temperature controlled environment would eliminate the risk completely.

The calorimeter, with its two-chamber design and the ability to accommodate different kinds of ceilings, allows all common luminaire mounting methods. The two-chamber design also allows evaluating the heat distribution by the installed luminaire into ceiling and floor spaces.

There are, however, also some areas that show room for improvement. The commissioning process has shown that measurements with a thermal input of less than 50 W show significant errors of 30.8 % (10 W) and 33.7% (25 W). This is caused by a variety of factors. First of all, even though the U-Value of the calorimeter is very low, it still has a huge surface area leading to a heat loss of several Watts if there is a temperature difference in the range of 2-5 K between the inside and outside. This heat cannot be accurately accounted for. If at any time, another calorimeter for low wattage luminaires should be constructed, reducing the size and therefore the surface would help increase the accuracy.

Another factor is the accuracy of both the temperature sensors and the anemometers. At their initial accuracy, the temperature sensors used fitting for the application. Due to the drift of accuracy, their accuracy has decreased, however. A calibration of the existing sensors or the acquisition of even more accurate temperature sensors could increase the overall accuracy of the calorimeter measurements. Though, the weaker part of the measurement is the two anemometers. Measuring air-flow accurately is a great challenge, much greater than measuring the flow of a fluid such as water. As explained earlier, there are different ways of measuring air flow, but they all have shortcomings regarding the calorimeter application and at this point, the vane anemometer is the most suitable. In the future, there may be more accurate vane anemometers or other kinds of anemometers that are suitable for the application.

Another option for a future calorimeter would be installing heat exchangers in the calorimeter and use water to remove heat from the calorimeter chambers. In each of the two cavities, one heat exchanger would be installed. The heat exchanger would be part of a closed-loop water circulation with a pump, two temperature sensors, a volume-flow meter and a secondary heat exchanger on the outside. The secondary heat exchanger on the outside would be used to cool down the water before it is being pumped into the calorimeter again to remove heat. Similar to the method used in this calorimeter, one temperature sensor would be installed where the water circulation enters the calorimeter and one where it exits. With the temperature difference and the mass flow of water, the heat removed can be calculated. The advantages of using water as a medium to remove heat compared to air are that water is an incompressible fluid, therefore, measuring the volumetric flow rate with a low error is easy and not expensive and no humidity measurement and calculation is needed.

The easiest fix, at this point, for the issue with luminaires smaller than 50 W is installing multiple of the same kind in the calorimeter.

Another change that could be made is improving the controllability of the fan speed. Currently, MTP-10 controllers are used which allow airspeed control through a rotary switch. Setting both fans at the correct, similar airspeed can be challenging at times. There are 0-10V controllers available which can be connected to a computer. The voltage can then be set to the exact value wanted in a computer software.

Concluding, this calorimeter can be considered a success as it is the first of its kind. It allows for accurate measurement of thermal outputs of 50 W or greater. Due to its spacious design, it may also allow evaluating thermal performance of other items outside the field of lighting.

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